CHALLENGES OF ARRAY PROCESSING FOR DEEP SPACE TELEMETRY, NAVIGATION AND COMMAND APPLICATIONS

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Abstract— The NASA Deep Space Network is considering different approaches to replenish its best but aging asset - the 70-meter antennas. Among options being studied are various array configurations, each comprised of a varying number of array elements of different aperture (e.g., 34-meter parabolic versus 5-meter parabolic versus half-wave dipoles). All array configurations, however, share a common set of technical challenges that are not encountered by the single-aperture approach. For telemetry application, it is the ability to coherently correlate and combine extremely weak signals received at each array element. For navigation, the challenge is to maintain the integrity of ranging measurements. And for commanding, it is the ability to establish and maintain coherence among multiple transmitters. This paper describes the context of these challenges and identifies some possible methods, as appropriate, in meeting them.

1. INTRODUCTION

Communications and navigation support to NASA space exploration and scientific research is provided by the Deep Space Network (DSN). The DSN comprises of a set of tracking stations with antennas of various aperture. Each group, often referred to as subnet, is distributed evenly around the world to provide continuous global communications with spacecraft. The smallest subnet is the set of 11-meter antennas, specifically designed to support the space very long baseline interferometry (Space-VLBI) applications. The next group, the 26-meter antennas, is mainly used for Earth orbiter missions. At the next increment, the 34-meter subnet covers deep space missions typically up to Mars distance as well as high-Earth orbiters. Lastly, there is the 70-meter subnet. Missions that explore the outer planets in the solar system and require a reasonably high science data return, such as Cassini, or those that involve travel in the interplanetary region, such as Voyager, critically rely on the 70-m antenna resource.

The 70-meter antennas were built in the late 1960s and early 1970s, with an original aperture of 64-meter. They were later expanded to 70-meters in the late 1980s to provide better support to Voyager's Uranus and Neptune encounters. These antennas were designed for a 15-year operating life cycle. As the structures age, concern for the viability of their operation is heightened. When the mechanical components for these large antennas fail, the downtime for repair can be long, on the order of weeks and months in the most extreme cases. . These outages in service then negatively affect the mission operations.

As the DSN community investigates the alternatives for 70-meter antenna replenishment, and how best to accomplish it given today technology, one major contender is building an arraying of several smaller apertures as opposed to a single monolithic aperture. The arraying concept is symbolically represented in Figure 1. By properly phasing and combining signals received from multiple smaller aperture antennas, one can achieve the equivalent of a single larger aperture.

Several options exist within the array approach. Two configurations that are deemed most viable within current cost and technology constraints are (1) an array of four 34-m antennas [1] and (2) an array of 200 elements of 5-m aperture [2]. Both of these options employ parabolic reflectors. Other array options are also being considered. Most notable are the concepts of a reflectarray [3] and a phased-array [4]. While the arguments made in this paper apply to all array configurations, comments made to illustrate a point will be referenced to the configuration

of four 34-meter antennas and 200 elements of 5-meters.

The remainder of this paper focuses on the technical and operational considerations of an array configuration. Section 2 discusses the benefits of arraying from both performance and programmatic viewpoints. Sections 3, 4, and 5 address the technical challenges associated with telemetry, navigation, and command applications and suggest possible solutions as appropriate. Section 6 focuses on the challenges affecting system operability. A summary of this paper is provided in Section 7.
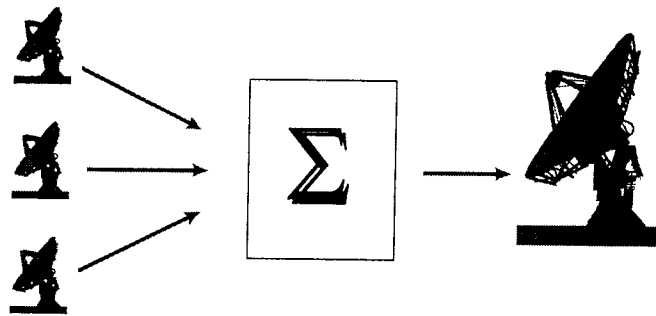

Figure 1 Array concept illustration

2. ADVANTAGES OF ARRAYING

Arraying holds many tantalizing possibilities: better performance, increased operational robustness, implementation cost saving, more programmatic flexibility, and a broader support to the science community. Each of these topics is further discussed below.

1. Better performance

For larger antennas, the beamwidth is naturally narrower. As a result, antenna pointing error becomes more critical. To stay within the main beam and incur minimal loss, antenna pointing has to be more precise. Yet this is difficult to achieve for larger structures.

With an antenna array configuration, antenna pointing error is not an issue. The difficulty is transferred from the mechanical to the electronic domain. The wider beamwidth associated with smaller aperture of each array element makes it more tolerant to pointing error. As long as the combining process is performed with minimal signal degradation, an optimal gain can be achieved.

Arraying also allows for an increase in effective aperture beyond the 70-meter capability in order to provide support for a mission at the time of need. In the past, the Voyager mission relied on arraying to increase its data return during Uranus and Neptune encounters in late 1980s. The Galileo mission is another recent example where arraying was used to increase the science data return by a factor of 3. (When included other improvements, such as a better coding scheme, data compression and a reduction of system noise temperature, a total improvement of a factor of 10 was realized.)

Future missions can also benefit from arraying. These include the class of missions that, during certain operational phases, require more performance than what a single-antenna can offer. For example, the Cassini mission requires only a single 34-meter antenna during cruise phase, but upon entering the Saturn orbit, in order to return 4 Gbits/day mapping data, it will need an array of a 70-meter and a 34-meter antenna[5]. Missions that need to relay critical science data back to Earth in the shortest possible time also can benefit from antenna arraying. The Stardust mission, for example, can reduce single-event risk by increasing the data rate for its encounter with the Wild 2 comet in 2004.

2. Better operability

2

Arraying can increase system operability. First, a higher resource utilization can be achieved. With a single aperture configuration, a shortfall in the 34-meter link performance will immediately require the use of the 70-meter antenna. As a result, there exists the potential for over-subscription of the 70-meter service. In the case of array, however, the set can be partitioned into many subsets supporting different missions simultaneously, each tailored according the link requirements. In so doing, resource utilization can be enhanced.

Secondly, arraying offers maintenance flexibility. Supposed the array is equipped with 10% spare elements. The regular preventive maintenance can be done on the rotating basis, allowing the system to be fully functional all times.

Thirdly, the cost of spare components would also be smaller. Instead of having to equip the system with 100% spares in order to realize a system that is fully functional around the clock, the array offers an option of furnishing spares at a fractional level.

Equally important is the robustness of operations. With a single resource, failure tends to bring the system down. With an array, failure in each array element degrades system performance but does not cause a service shutdown.

3. Implementation cost saving

The cost saving is realized from the fact that smaller antennas, because of their weight and size, are easier to build. Since multiple commercial vendors can produce the antennas on a large scale, competition will further bring the cost down.

It is well known the construction cost of an antenna is proportional to roughly the cubic power of the antenna size. The reception capability of an antenna, however, is proportional to the area of capturing surface, which is the square of the antenna diameter. Thus, halving the antenna aperture reduces the construction cost of a single antenna by a factor of 8 while requiring a construction of four array elements. The net advantage is an approximate 50% cost saving. Proper accounting, however, needs to take into account the extra cost of electronics required at multiple antenna elements instead of one, as in the case of a single antenna.

4. Programmatic flexibility

With arraying, the programmatic flexibility is reflected from the fact that additional elements can be incrementally added to increase the total aperture at the time of mission need. This option also allows for a spread in required funding and minimizes the need to have all the cost incurred at one time. The addition of new elements can be done with little impact to the existing facilities that support ongoing operations

5. Cross support to science applications

An array provides features that can be exploited to support science applications that rely on interferometry, such as VLBI and radio astronomy. In the case of a 200-element array, the DSN implementation would be synergistic with the international Square Kilometer Array (SKA) effort by serving as a testbed for demonstration of capability, albeit on a smaller scale.

3. CHALLENGES IN TELEMETRY PROCESSING

The major challenge in arraying is to properly align signals received from different antennas. This process, referred to as correlation, involves the detection, and correction, of the phase difference among the inputs. In an ideal case, the signals arriving at different antennas are delayed only by the difference in the geometrical paths. The Earth troposphere, however, is turbulent and has a structural function that varies spatially and temporary. The varying index of refraction causes a distortion in the signal wavefront. The goal of correlation processing between the array elements is to estimate this variation among the different antenna inputs and allow it to be

removed. The signals then can be properly combined with optimal results.

Performance of the correlation is dependent on signal strength. When the signal is sufficiently strong, correlation can be achieved rather easily. When the signal level is low, one can maximize the probability of detection by: (1) extending the signal integration time, (2) using an improved method of correlation, and (3) using other sources besides the spacecraft being tracked, for calibration. Each option is further discussed below. Note that the correlation threshold is dependent on the aperture of the array element. The smaller the antenna, the more difficult is the correlation process. To achieve reliable phase detection with a precision such that the combining loss to the arrayed signal power would be less than 0.2 dB, a minimum correlation signal-to-noise ratio of 14 dB (referenced to power, instead of voltage) is needed.

Extending integration time

Unfortunately, because of the time varying nature of the wet troposphere, there is a limit on the maximum integration time. At the operating Ka-band frequency, the limit for a 20-deg correlation phase error at short antenna baseline is about 20 seconds. [6]

Improving on correlation methods

With sufficient signal strength, a pair-wise correlation can be done between the reference antenna and any other element in the array. This is the most desired method since the processing is straight forward and relatively fast. When the signal is not strong enough, however, correlation needs to be done between each of the array elements and the sum of all antennas. By leveraging on the sum of all antennas, the correlation signal-to-noise ratio is improved, resulting in a better phase estimation; however, depending on the available signal level, convergence to the final answer may require a few iterations.

Use of other calibration source

When spacecraft signal is below the detection threshold, calibration of tropospheric variation can be done using a stronger radio source in the directional vicinity of the spacecraft. A small fraction of the antennas, say 10%, can be directed toward nearby calibration radio source to determine the distortion of the signal wavefront. Care must be taken to ensure an even geographical distribution of calibrating elements across the whole array configuration so that a good sampling of the distorted wavefront can be obtained. The calibration measurement can then be used for the removal of phase variations in the antennas tracking the spacecraft. In transferring the phase measurement from calibrating antennas to the spacecraft-observing antennas, the electronic phase drift over time between the two sets needs to be accounted for. Either the receivers are to be designed with sufficient stability, or their variation must be monitored and compensated. Another possible approach for minimizing this effect is to rotate the assignment of calibration elements and spacecraft-tracking elements within the observation period.

How widely available are the radio sources in the direction of a spacecraft? The answer depends on the size of the array elements. The larger the aperture, the narrower the beamwidth and the higher antenna gain. More close-in calibration source would be needed, but the source need not be as strong. Conversely, the wider beamwidth of smaller aperture provides more spatial coverage, thus increasing the odds of finding appropriate sources in the direction of spacecraft. The drawback, however, is that a stronger source is needed. Based on (1) the expected antenna gains and system noise temperature, (2) radio source distribution as a function of source flux density at various frequency bands, and (3) the data for tropospheric fluctuations at Goldstone, it has been determined that for 5-meter aperture, there are sufficient calibration sources to keep the coherence loss below 0.2 dB for 98% of the time, even at Ka-band. [7] Such a luxury, however, does not exist in the 34-meter array configuration. An alternative would be to implement a water vapor radiometer at each of the four 34-meter antennas. The radiometer, as the name implies, directly measures the water content along the line of sight. Although it is a bit costly, the cost is offset by the fact that only four units are required.

4

4. CHALLENGES IN NAVIGATION

Navigation precision is dependent on the measurement of the phase between the transmitted and received signal. The accuracy of this measurement is dependent on the signal bandwidth. Spacecraft signal, unlike radio source in radio astronomy observation, is bandwidth narrow. A typical spacecraft transponder bandwidth is in the order of 1 MHz. In some instances where a greater accuracy is required, spacecraft may need to generate a series of wide spectral tones to aid with ranging measurement.

Proper accounting also needs to be given to any phase shift introduced into the combined signal by array processing. For example, because of causality effect, the data alignment in array can only be done with a positive delay line (i.e., the signal can only be delayed, but not sped up). Since the relative delay among the array elements is changing during the track, it is necessary to introduce a fixed delay bias into the system, then to adjust the ever-changing relative delay from that reference point. This bias needs to be appropriately compensated for in the final ranging data, and telemetry data as well.

In addition, consideration needs to be given to the choice of reference for correlation. In DSN communications, ranging and telemetry signal typically have different characteristics. Missions usually opt to devote more signal power to telemetry modulation, leaving little to ranging. Telemetry modulation, however, is often of lower bandwidth compared to ranging modulation. Also, telemetry signal contains only one-way Doppler, whereas ranging signal is imbedded with two-way Doppler. All of these distinctions imply that telemetry signal has a different signature than ranging signal. Thus, if arraying is performed based on telemetry information, as often is the case because of the interest in minimizing the degradation on telemetry data, there would be an greater error in the ranging data. Care must be taken to minimize this error, either by special considerations in signal processing or by setting up two separate paths of correlation and combining at the cost of additional equipment.

5. CHALLENGES IN COMMANDING

To maintenance communications with spacecraft under normal conditions, the DSN currently requires a 20 kW transmitter at X-band on the 70-meter antenna. One can envision, however, a need for even greater transmitting power to provide for emergency support to a spacecraft that cannot maintain its attitude or to support future missions that venture out into the further reaches of interplanetary space.

If one single array element were to serve as the transmitting antenna for the entire array, its smaller aperture would require an increase in transmitting power in order to preserve the effective isotrophic radiated power (EIRP) received at the spacecraft. The required power increase is proportion to the square of the ratio of the effective total arrayed aperture and the physical aperture of a single element. As a result, 80kW is necessary on the 34-meter antenna and 4 MW is needed on the 5-meter antenna. Obviously, this poses a problem. Such a transmitter would be more complex to build and more costly to operate. In addition, there is also a radiation safety issue. The radiating power in the near field would exceed the recommended safety level for radiation exposure at microwave frequencies for the operations crew on the ground and for any aircraft that might travel inside the air corridor of the beam.

Given the above considerations, it is necessary to consider uplink in an array configuration. Since current spacecraft do not have the mean to align the signals received from different transmitting antennas, the alignment has to be done on the ground. This correction needs to account for instability in the uplink electronics and tropospheric variation.

Electronic stability

The integration time required for detection of a ranging signal in the DSN operating environment can be as long as 1000 seconds. The uplink electronics must be designed to be sufficiently stable over this time frame. This

stability can be achieved with proper design of the electronic components or with proper compensation for the measured drift.

Counteracting the tropospheric variation

Two approaches can be used to compensate for tropospheric variation. The first is to use the measured variation obtained from downlink processing. Since it is the Earth tropospheric effect that is to be removed, as long as the latency in data processing is smaller than the 20-second time constant of tropospheric variation, the transfer of information from downlink to uplink is valid. Obviously, this option is constrained by the availability of a downlink signal. It also introduces an acquisition delay on the uplink path.

Another approach is to bounce a radar signal to debris objects in low-Earth orbits and determine the tropospheric variation based on the received echo. Such a scheme is described in [8] for two 34-meter antennas and 5 kW peak transmiter. (Note however that additional work still needs to be done to demonstrate such a capability for the 5-meter arraying. The difference arises because many more transmitting elements would be involved and the transmitting power, because of radiation safety limit, would be at a lower level.) The drawback with this scheme, compared to the use of downlink information, is the need for additional equipment for radar signal processing.

In both cases, the transfer of information needs to account for the difference in the operating frequency between uplink and downlink. In deep space applications, the frequency difference is on the order of $1 - 2$ GHz.

6. OPERATIONAL CHALLENGES

Because of the interactive nature of space mission operations, the ground support is often time-sensitive, and sometimes time-critical. For example, critical events that affect its trajectory, such as planetary encounter, orbital insertion, entry/descent/landing onto planetary surface, all require fast turn-around data processing so that appropriate action can be taken in the next activities in mission design. This constraint on real-time processing has an implication on the design of arraying. Among the items to be considered are signal bandwidth to be captured and latency in the data processing. The design also needs to address issues associated with signal distribution, power consumption, and other infrastructure factors. An optimal design must account for these performance and cost concerns.

Another consideration is the effort required for calibration. Calibration activity takes away available track time, thus affecting the network utilization. The delay due to the required calibration and signal acquisition needs to be as short as possible, on the order of a few minutes or less. For the array to be effective, the design also has to automate the process of calibration so that it is not labor intensive.

Finally, with many elements involved in an array configuration, the monitor and control design needs to be automated and working flawlessly. Its operation load should require only one operator, as is in the case of single-aperture antenna. This constraint applies both to a four 34-meter as well as a 200-element array. Also, automatic identification of failure in each array element is needed to facilitate the maintenance effort.

7. CONCLUSIONS

In summary, this paper identifies several aspects of antenna arraying that makes it attractive. Among these possibilities are: (1) an increase in the overall network utilization because the ground resources can be configured in smaller increments to better match the required link margin, thus allowing the extra resources to be diverted toward other support; (2) an improvement in system operability such as graceful degradation against failure, continuous operations while part of the system is being maintained or repaired, reduction on the amount (and cost) of spares required; (3) a lower implementation cost due to the ease in constructing smaller antennas; (4) a

flexibility in programmatic planning wherein additional aperture can be deployed at the time of need rather than all up front; and (5) a cross-enterprise support to science community.

This paper also identifies several technical and operational considerations in the design of an array system so that it can be responsive to the needs of deep space communications and missions operations. Most important is the ability to correlate and combine telemetry signals that are often low in power andnarrow in bandwidth and to do so with minimal processing loss. Maintaining the accuracy of navigation data is equally important in light of the fact that ranging signals often must co-exist with telemetry signals and is given only a small portion of the signal power. And because of radiation safety consideration, uplink for command and navigation purposes must be done in an array configuration as well.

Regarding operational considerations, real-time processing of data is required to better meet the needs of mission operations for time-critical events. The operation of arraying, in terms of monitor and control forboth spacecraft tracking as well as calibration activities, needs to be streamlined and automated so that it has minimal or no impact on operations personnel. The time required for calibration activities must be brief so that it does not negatively impact network utilization.

Overall, it is our belief that none of the issues identified above is insurmountable. Rather, by identifying them in this paper, we hope the designer of any future array implementation will be able to deliver a system that is most responsive to the needs of deep space communications and operations.

ACKNOWLEDGMENTS

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BIOGRAPHY

Timothy Pham *is a senior member of the technical staff at the Jet Propulsion Laboratory. He is currently the manager for the Deep Space Network system engineering within the Telecommunications and Mission Operations Directorate, as well as the project element manager for the implementation of the new 34-meter deep space station to be deployed at Madrid. He recently served as project manager for the development of antenna arraying capability for the DSN. Other past contributions include system engineering for Goldstone Solar System Radar, radio science, and Galileo telemetry systems. He received a BSEE from the California Institute of Technology and a MSEE from the University of Southern California.*

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